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Liquid Wall Chambers

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Liquid Wall Chambers*

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Request for Information on Topical Areas in Inertial Fusion Energy Sciences
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Liquid Wall Chambers

Description

The key feature of liquid wall chambers is the use of a renewable liquid layer to protect chamber structures from target emissions. Two primary options have been proposed and studied: wetted wall chambers and thick liquid wall (TLW) chambers.

With wetted wall designs, a thin layer of liquid shields the structural first wall from short ranged target emissions (x-rays, ions and debris) but not neutrons. Various schemes have been proposed to establish and renew the liquid layer between shots including flow-guiding porous fabrics (e.g., Osiris, HIBALL), porous rigid structures (Prometheus) and thin film flows (KOYO). The thin liquid layer can be the tritium breeding material (e.g., flibe, PbLi, or Li) or another liquid metal such as Pb.

TLWs use liquid jets injected by stationary or oscillating nozzles to form a neutronically thick layer (typically with an effective thickness of ~50 cm) of liquid between the target and first structural wall. In addition to absorbing short ranged emissions, the thick liquid layer degrades the neutron flux and energy reaching the first wall, typically by ~10×x, so that steel walls can survive for the life of the plant (~30-60 yrs). The thick liquid serves as the primary coolant and tritium breeding material (most recent designs use flibe, but the earliest concepts used Li). In essence, the TLW places the fusion blanket inside the first wall instead of behind the first wall.

Status

Conceptual designs exist for wetted-walls (OSIRIS, HIBALL, KOYO-F) and thick-liquid (HYLIFE-II Robust Point Design, Z-IFE). The most developed TLW design is the HYLIFE-II chamber. HYLIFE-II used an array of oscillating jets of molten salt flibe to shield the steel walls of a heavy ion fusion chambers. The Robust Point Design (RPD) was the last integrated design study for the TLW chamber. The Z-IFE study developed a TLW concept compatible with pulsed-power driven, high yield targets at low pulse repetition rate (~0.1 Hz). The Japanese Koyo-FI is the most recent wetted wall design and is based on a laser driver with fast ignition targets.

University scale experiments in support of liquid wall chambers were conducted at UC Berkeley and Georgia Tech. UCB experiments demonstrated various aspects of the flow configuration and response to disruptions simulating an IFE target blast. These included creating high quality individual jets with clean surfaces and no drop spray, arrays of flowing jets, oscillating jet arrays, high explosive blast disruption of jet arrays, thin vortex flow to protect beam port surfaces and thick vortex flow as an alternative to the array of jets. This experimental work was complimented with computational modeling of the ablation of the inner surface of the liquid and subsequent venting through the array of jets leading to a pressure pulse on the first wall. Georgia Tech work (modeling and experiments) focused on stability of thin film flow, drop formation and control, and flow around protrusions to simulate beam port penetrations.

Current R&D

There has not been significant R&D on TLW since the 2002 RPD and work on the TLW chamber for Z-IFE (2004-2006) with the exception of the thick vortex flow concept development and experiments at UCB. Work on wetted walls ended with the ARIES IFE study (2004).

R&D Goals and Challenges

The key goals of R&D in this area would be to 1) demonstrate the ability to create the protective liquid configuration in the first place, 2) determine the response of the liquid to the fusion yield (including response to neutron energy deposition) and the ability of the TLW to mitigate shock and debris, and 3) show that the protection can be re-established prior to the next shot while assuring ability for target and driver energy delivery. The difficulty of meeting these requirements depends on the driver approach whether laser, HI or Z. Detailed R&D plans were previously developed for TLW chambers and should be re-evaluated. Because the ablation and neutron heating occur on a time scale that is much shorter than hydrodynamic response, subscale tests with simulant fluids and non-fusion impulse loads can be used to test key issues of response and reestablishment of the liquid protection. Chamber clearing needs to be studied theoretically and experimentally, especially in the vortex chamber configuration.

Related R&D Activities

Other R&D related to tritium breeding and recovery, power removal and conversion, safety, etc. are more generic with other chambers using the same liquid breeder. These are seen as less critical than the issues related to the liquid dynamics.

Recent Successes

See description of University experiment under “Status” above. Recent work at UCB has demonstrated thick liquid vortex flow as a possible alternative to injected free jets for the thick liquid wall. The vortex will have lower pumping power needs compared to the oscillating jets. The pressure caused by sudden expansion of the liquid by neutron heating would be reduced by either injection of gas bubbles or by use of gas filled bladders towards the back of the vortex. Also, in the 2004-07 timeframe the TLW design was adapted for Z-IFE.

Metrics

Key metric for liquid chamber are the related the goal of chamber protection and ability to operate at desired target yield and pulse repetition rate for long periods (decades) without replacement of chamber structures. The R&D goals given in the 1999 NAS report are still largely valid and some are reproduced here:

Near Term <5 years. The major near-term liquid-wall R&D goal is resolution of remaining *feasibility* questions, providing confidence in prospects of long-term success to support the decision to proceed with integrated research experiment(s) (IREs) for HI, Z and/or laser drivers. The R&D described in the 1999 NAS report is still valid and includes activities on the following topics: systems studies; liquid-jet hydraulics; wetted-wall hydraulics; ablation/ venting/ condensation; superconducting magnet shielding and thermal response, Z-IF RTL insertion mechanism shielding; laser final optics protection; flibe and liquid metal chemistry, corrosion, EOS and tritium recovery.

Midterm ~10 years. Success would be experimental validation of models required to extrapolate to prototypical chamber conditions, coupled with integrated system designs meeting clearing rate and other metrics. Presuming that thick liquid will be found viable, during this period three major experimental activities occur to provide *engineering-design* capability: Integrated ablation/venting/condensation experiments, e.g. minichambers scaled to prototypical energy densities and tested on NIF or pulsed power machines; integrated liquid hydraulics experiments to demonstrate liquid-pocket formation, destruction with scaled explosive charges, and pocket reestablishment; beam propagation experiments to study of the effects of background gas density and residual liquid droplets on heavy-ion/laser beam propagation under prototypical chamber conditions.

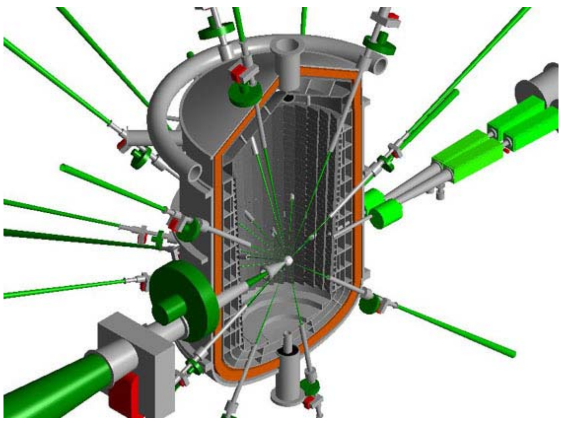
Long Term >20 years. With adequate budgets, liquid-wall target chambers operating at 0.1 to 10 Hz can be made available for the ETF and subsequent IFE demonstration and commercial fusion power plants.

Principle Steps to a DEMO Plant

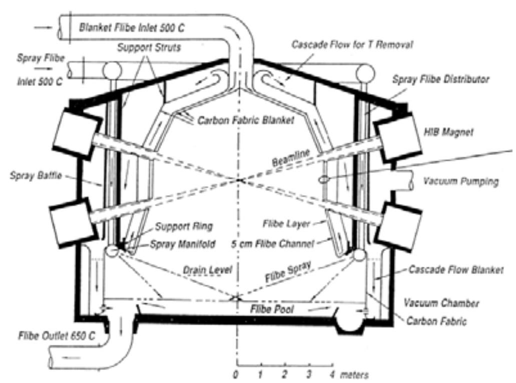
With regard to liquid chambers, the above encompass steps to a demo.

Proponents' Claims— Proponents claim that thick-liquid walls can reduce the need for expensive materials testing programs and with their compact geometry can provide major advantages for capital cost, availability, heat removal, and tritium control and recovery. If this is true, a modest investment to prove the concept feasibility (primarily hydrodynamics) will save significant R&D funds and the time needed for radiation damage resistant material development.

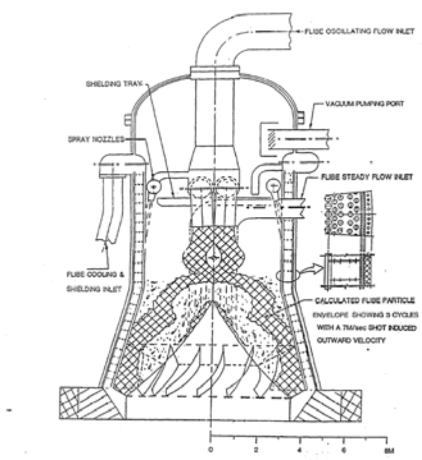
Critics' Claims—Critics claim that debris condensation and droplet clearing rates will prove too low for high repetition rates; for HIs, that background gas densities will be too high for beam propagation; and for lasers, that ablated liquid will condense on the transparent vacuum interface.



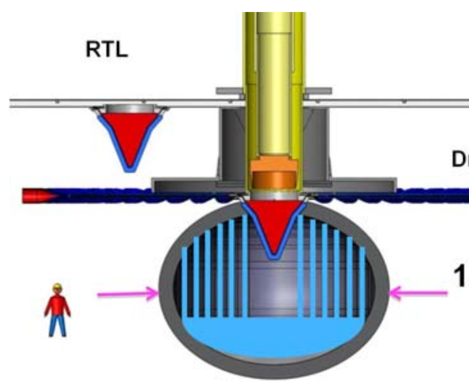
Koyo-F wetted wall chamber



Osiris wetted wall chamber



HYLIFE-II Thick liquid wall chamber



Z-IFE Thick liquid wall chamber

Subtopics for Liquid Wall Chambers

The request from NAS suggested including comments on a variety of subtopics. Here we briefly summarize IFE relevant research in these areas in the context of liquid wall chambers.

Blanket and Tritium Systems

As noted above, the liquid used in thick liquid wall chamber designs must also be the tritium breeding material. Options include Li, PbLi and molten salts such as flibe and flinabe. The most recent designs for heavy ion and Z drivers both use flibe. The liquid used for TLW protection also serves as the primary coolant. Since the flow rate required for wall protection is typically large (as in HYLIFE-II), only a portion of the flow needs to be circulated through the heat transfer system and tritium recovery system on each pass.

For a wetted wall, the wall protection and breeding functions can be separated; the first wall liquid does not have to be a tritium breeding material. The Prometheus wetted wall design used liquid Pb for wall protection and a He-cooled solid breeder. Other wetted wall designs use the same liquid for wall protection and in the breeding blanket (e.g., Osiris and Koyo-F).

There is currently no IFE-specific R&D on blankets and tritium breeders. The international MFE community is working on a variety of tritium breeding materials and blanket designs, and some of that work is relevant to liquid wall chambers. Both the US and EU are working on PbLi as a breeding material. A Li option is still being considered by some of the ITER partners, but not in the US. Also, there is little if any work on flibe in the MFE community.

High-Heat-Flux Components

A key feature of the liquid wall chambers is that the liquid absorbs the intense heat flux from the fusion source. Thus this subtopic is not particularly relevant to liquid wall chambers.

Radiation-Damage-Resistant Materials

Depending on the design, wetted wall chambers will need, or at least benefit from, the development of structural materials that perform well in the intense fusion neutron environment. The thin liquid layer does not provide any significant shielding for the underlying structures. Therefore, the first structural wall and blanket structures will periodically have to be replaced. Worldwide R&D on understanding radiation damage mechanisms and developing more radiation resistant steels will benefit these IFE designs. There is currently no IFE-specific R&D on radiation damage to materials.

Some wetted wall designs have sought to minimize the need for long life materials. For example, the Osiris and HIBALL designs use porous fabric structures filled with liquid to deliver and feed the protective liquid layer. These were designed to be rapidly replaced when needed and did not serve critical functions such as providing the vacuum barrier.

Thick liquid wall chambers by design minimize or perhaps eliminate the needed for the development of radiation damage resistant structural materials.

International Fusion Materials Irradiation Facility (IFMIF)

The IFE community has not been actively engaged in considerations or arguments for building the IFMIF. Designers either avoid or minimize the need for such a materials testing facility or propose doing radiation damage testing in an early, high average power IFE facility.

Shields

Additional shielding beyond the breeding blanket is typically needed for any fusion design, IFE or MFE, and may be integrated with fusion chamber and breeding blanket and/or include surrounding special shielding materials and structures (e.g., concrete walls to provide the biological shield). For MFE, a major shielding requirement arises from the need to protect the superconducting magnets. For heavy ion driver, special attention must also be paid to shielding the final focus magnets, but this has been shown through detail neutron transport analysis to be doable. Computational tools are sufficiently advanced to analyzed and determine shielding requirements for fusion plants. This is not viewed as a high priority R&D need.

Remote Maintenance

Components in the vicinity of any fusion chamber will be become activated within a short time of the start of operation of the plant, so remote maintenance capability will be required. This requirement is not unique to IFE or to liquid chamber designs. The degree of RM will vary with design details, e.g., if the TLW chamber can last for the life of the plant, RM will not be required for that component. However, it is likely that remote inspection will be required and it may be prudent to design and include RM capability even if the particular design expects minimum needs. Systems developed for MFE, including ITER, will benefit IFE in general. There is currently no IFE specific R&D on RM systems.

Safety and Environment

Safety and environment (S&E) considerations will play a key role in the success of fusion energy. Over the last decade, significant progress has been made in the area of S&E studies for Inertial Fusion Energy (IFE), with the goal of optimizing its safety and environmental characteristics. The basic safety principles for achieving this goal are: (1) avoidance of public evacuation during worst-case accidents, (2) protecting the workers from ionizing radiation by keeping exposures as low as reasonably achievable (ALARA), and (3) minimizing the amount of radioactive waste that would pose a burden for future generations. Based on these principles, IFE S&E assessments have been focused on the following areas:

- understanding the behavior of the largest sources of radioactive and hazardous materials in an IFE facility (e.g. tritium, activation products);
- understanding how energy sources in an IFE facility (e.g. decay heat, chemical reactions) could mobilize those materials;
- development of integrated state-of-the-art analytic tools and models to describe the behavior of a fusion facility under normal and off-normal conditions and assess quantitatively potential impact on the workers so as on the public and environment.

Within this scope, several studies have been published in the past that assess the safety and environmental issues associated with IFE designs using thick liquid wall chambers [1-3]. Such analyses have used a state-of-the-art methodology specifically developed for IFE by adapting and adopting computer codes and methodologies traditionally used in Magnetic Fusion Energy (MFE) [4]. This methodology included updated activation codes and data libraries for radionuclide inventory evaluations, heat transfer codes appropriately modified for an enhanced representation of structural material oxidation, and thermal-hydraulics models capable of simulating a wide range of physical phenomena including aerosol physics, and tritium and aerosol transport and release. Analysis of accident consequences, including doses to the public, has been performed for a range of accident scenarios, using available oxidation-driven mobilization data from experiments at the Idaho National Laboratory (INL) [5,6]. The results of these studies show that compliance with the safety objectives is achievable through integration of safety considerations since the early design stages. The accident analysis results indicate that tritium release is the dominant hazard, and therefore the confinement of tritium inventories throughout the facility becomes a key safety function.

Fundamental not only to the economics of IFE but also to many waste management scenarios is the survivability of structural materials under intense neutron fluxes. A significant safety advantage of thick liquid wall designs is that the neutron damage to chamber structures can be reduced considerably due to the shielding provided by the liquid. This allows for a reduction of the waste stream as the need for replacement of the chamber structures can be minimized, resulting in a simplification of the waste management requirements [7].

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Appendix to Liquid Wall Chambers

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